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Low Cardiac Output Syndrome After Pediatric Congenital Heart Surgery: A Contemporary Scoping Review from Mechanisms to Emergency Mechanical Support

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Abstract

Context: Low cardiac output syndrome (LCOS) affects up to 25% of children after congenital heart surgery and remains a major cause of morbidity. While temporary mechanical circulatory support (tMCS) options have expanded, with ECMO remaining the cornerstone and Impella emerging as an adjunct in selected older children, comprehensive evidence synthesis integrating pathophysiology with contemporary multicenter outcomes is lacking. This scoping review maps current evidence on the pathophysiology, early recognition, and evolving tMCS strategies for pediatric post-cardiotomy LCOS, with emphasis on developmentally appropriate approaches.

Evidence Acquisition: Following Arksey and O'Malley's framework and JBI methodology, we systematically searched PubMed/MEDLINE, Scopus, and Web of Science (January 2015 to October 2025). Inclusion criteria: original research, systematic reviews, meta-analyses, and consensus statements on pediatric (0–18 years) post-cardiotomy LCOS managed with pharmacological support or tMCS. Data were narratively synthesized with a focus on multicenter collaborative evidence.

Results: From 847 initially identified records, 42 studies met the inclusion criteria. Pediatric LCOS pathophysiology differs fundamentally from that of adults due to myocardial immaturity, single-ventricle physiology, and lesion-specific hemodynamics. The 2025 meta-analysis (N=1,200) demonstrated that levosimendan reduces the incidence of LCOS compared with milrinone (RR 0.67, p=0.001). The ACTION collaborative (N=150, 29 centers) reported 89.3% positive outcomes with Impella (preliminary registry data, presented at the 2025 ACTION annual meeting) (32.7% recovery, 32% bridge-to-transplant, 23.3% bridge-to-durable VAD). However, complications were 2.3-fold higher in patients <35 kg. ECPELLA achieved 45–62.5% recovery in adolescents.

Conclusions: Contemporary pediatric LCOS management requires developmentally tailored approaches integrating vigilant monitoring, targeted pharmacotherapy, and timely tMCS. Emerging collaborative network data are transforming care toward evidence-based practice. However, significant knowledge gaps remain in device-selection algorithms and the optimal timing of support initiation.

Keywords: Pediatric cardiac surgery, congenital heart disease, low cardiac output syndrome, mechanical circulatory support, extracorporeal membrane oxygenation.

1. Introduction

Low cardiac output syndrome (LCOS) following congenital heart surgery represents one of the most significant challenges in pediatric cardiac intensive care (1). Despite remarkable advances in surgical techniques, myocardial protection, and perioperative management, LCOS continues to affect approximately 25% of pediatric patients undergoing cardiac surgery and remains a major contributor to post-operative morbidity, mortality, and prolonged hospitalization (1-2). The pathophysiology of pediatric LCOS differs fundamentally from its adult counterpart. Children with congenital heart disease (CHD) present with developmentally unique considerations: myocardial immaturity with limited contractile reserve, vulnerability of specific anatomic substrates (particularly the single-ventricle circulation), and lesion-specific hemodynamic perturbations that vary dramatically across the spectrum of CHD (2).

The neonatal myocardium, with its reduced density of sarcoplasmic reticulum and increased dependence on trans-sarcolemmal calcium flux, exhibits distinct responses to ischemia-reperfusion injury and inotropic stimulation (3).

Over the past decade, the landscape of temporary mechanical circulatory support (tMCS) in pediatrics has evolved considerably (4, 5). While extracorporeal membrane oxygenation (ECMO) remains the most commonly used modality, particularly in smaller children, the introduction of transcatheter axial flow pumps (Impella) has expanded options for older children and adolescents (6, 7). The establishment of collaborative learning networks, most notably the Advanced Cardiac Therapies Improving Outcomes Network (ACTION), has enabled multicenter data collection and evidence generation in a field previously limited to small, single-center case series (8).

Despite these advances, a critical knowledge gap persists: existing literature comprises either focused physiological reviews or single-center case series, lacking an integrated synthesis that connects foundational developmental pathophysiology with the latest multicenter evidence from collaborative learning networks. Furthermore, rapid evolution in temporary mechanical circulatory support, particularly the expanding role of percutaneous axial flow pumps in pediatrics, has outpaced traditional textbook updates. This scoping review, therefore, aims to systematically map and integrate evidence across the continuum from pathophysiological mechanisms to contemporary mechanical support strategies, providing an evidence-based framework for the multidisciplinary team managing these complex patients.

2. Review Questions

This scoping review was conducted to answer the following questions:

1. What are the key pathophysiological mechanisms underlying LCOS in pediatrics with congenital heart disease, and how do they differ from adult post-cardiotomy shock?

2. What are the most recent evidence-based diagnostic and monitoring strategies for early identification and severity stratification of pediatric LCOS?

3. What is the current role of pharmacological prevention and treatment, including emerging evidence for Levosimendan versus Milrinone?

4. What are the contemporary indications, outcomes, and complications of temporary mechanical circulatory support (ECMO, Impella, hybrid strategies) in pediatric patients with refractory LCOS?

5. What is the optimal composition and function of the multidisciplinary team in managing these complex patients?

3. Methodology

3.1. Review Protocol

This scoping review was conducted in accordance with the Arksey and O'Malley framework (9) and followed the Joanna Briggs Institute (10) methodology for scoping reviews.

3.2. Search Strategy

We systematically searched PubMed, Science Direct, Scopus, and Web of Science from January 1, 2015, to October 31, 2025. The search strategy combined controlled vocabulary (MeSH terms) and keywords:

((("pediatric"(All Fields) OR "paediatric"(All Fields) OR "child"(MeSH Terms) OR "infant"(MeSH Terms) OR "adolescent"(MeSH Terms)) AND ("cardiac surgical procedures"(MeSH Terms) OR "congenital heart disease"(All Fields) OR "post-cardiotomy"(All Fields)) AND ("low cardiac output syndrome"(All Fields) OR "postoperative shock"(All Fields)) AND ("heart-assist devices"(MeSH Terms) OR "extracorporeal membrane oxygenation"(MeSH Terms) OR "Impella"(All Fields) OR "levosimendan"(All Fields) OR "milrinone"(All Fields)))

Additionally, we hand-searched the websites of the Advanced Cardiac Therapies Improving Outcomes Network (ACTION), the European Association for Cardio-Thoracic Surgery (EACTS), the Society of Thoracic Surgeons (STS), and the American Heart Association (AHA) for relevant guidelines and consensus statements.

3.3. Inclusion Criteria

Studies were included if they met the following PICAR criteria:1- Population: Pediatric patients (0–18 years) undergoing congenital heart surgery with post-operative LCOS.2-Concept: Pathophysiology, monitoring strategies, pharmacological management, or temporary mechanical circulatory support.3- Context: Post-cardiotomy setting in any healthcare facility.4- Types of evidence sources: Peer-reviewed original research (any design), systematic reviews, meta-analyses, clinical practice guidelines, and multicenter registry reports.

3.4. Exclusion Criteria

All studies with the adult population (>18 years) without separate pediatric data, Case reports, case series with <5 patients, conference abstracts, editorials, non-English publications, and studies focused on durable VADs as primary therapy without LCOS context were excluded.

3.5. Study Selection and Data Extraction

Two independent reviewers screened all titles and abstracts. Disagreements were resolved through discussion and, if consensus could not be reached, by a third reviewer. The inter-rater agreement at the full-text screening stage was excellent (Cohen's kappa= 0.89). The screening process was managed using EndNote X9. Data were extracted using a standardized form including: first author/year, study design, population characteristics, sample size, intervention/comparator, and key outcomes related to LCOS pathophysiology, monitoring, pharmacology, or mechanical support.

3.6. Data Synthesis

Given the anticipated heterogeneity, we performed narrative synthesis organized thematically around: (1) pathophysiological mechanisms, (2) monitoring strategies, (3) pharmacological management, and (4) temporary mechanical circulatory support. We prioritized multicenter collaborative data and recent meta-analyses to ensure contemporary relevance.

3.7. Search Results

The initial search yielded 847 records. After removing 234 duplicates, 613 titles/abstracts were screened, 189 full-text articles were assessed, and 42 studies met the inclusion criteria. Figure 1 illustrates the PRISMA flowchart diagram.

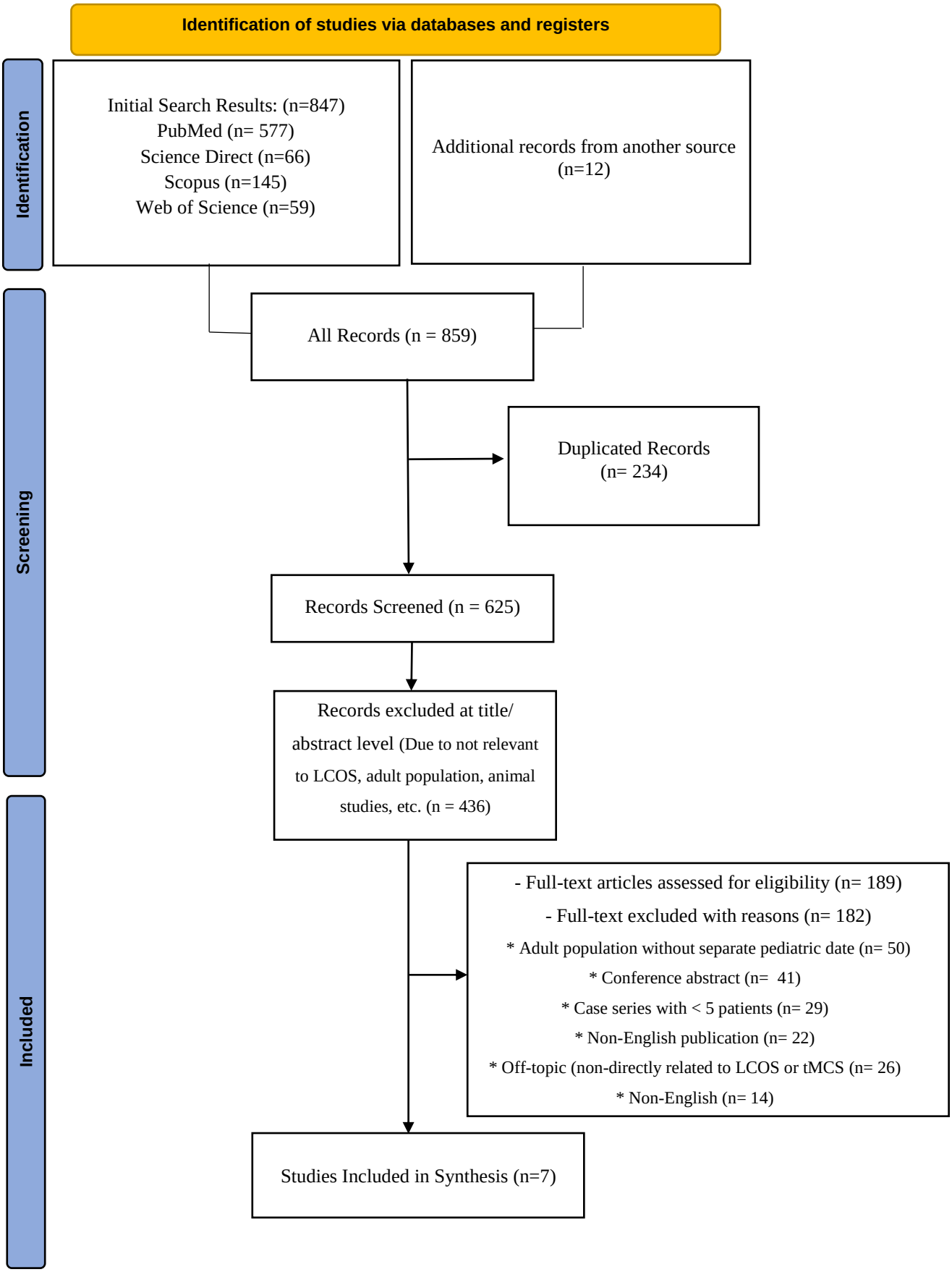

Figure 1. The PRISMA diagram of the study identification, screening, and registration

4. Results

The key studies from the 42 included studies, as presented below, are presented in Table 1.

Table 1: Key studies that summarize the results

First Author (Year)	Study Design	Population (N, Age/Weight)	Intervention/ Exposure	Comparator	Key LCOS-Related Outcomes	Level of Evidence*
Aslan N (2022)	Retrospective cohort	120 children post-CHD surgery	LCOS incidence and outcomes	No comparator	LCOS affects ~25% of pediatric cardiac surgery patients	II-3
Epting CL (2016)	Review	N/A	Pathophysiology of pediatric LCOS	N/A	Described myocardial immaturity, SIRS, and lesion-specific hemodynamics	V
Hoffman TM (2002)	Randomized controlled trial (PRIMACORP)	238 infants	Prophylactic milrinone	Placebo	Milrinone reduced LCOS incidence (primary evidence for prophylaxis)	I
Edelson JB (2025)	Multicenter registry (ACTION Network)	150 patients (median 15.3 yr, 62.9 kg)	Impella (5.5, CP, 2.5)	No comparator	89.3% positive outcome (32.7% recovery, 32% bridge-to-transplant, 23.3% bridge-to-durable VAD); complications 2.3Ã, higher if <35 kg (p=0.02)	II-2
Abraham D (2025)	Systematic review + meta-analysis	1,200 pooled pediatric patients (600 levosimendan, 600 milrinone)	Levosimendan	Milrinone	LCOS incidence reduced with levosimendan: RR 0.67 (95% CI 0.54-0.83, p=0.001); shorter ventilation and ICU stay	I
Wilkens SJ (2025)	Multicenter case series (ACTION ECPELLA)	20 patients (median 15.6 yr, 65.7 kg)	VA-ECMO + Impella (ECPELLA)	No comparator	45% recovery, 40% bridge to durable VAD, 5% transplanted; mortality 10%; hemolysis 50%, bleeding 20%	II-3
Lerner A (2025)	Single-center case series	8 adolescents (13-18 yr, 40-59 kg)	VA-ECMO + Impella (ECPELLA)	No comparator	62.5% myocardial recovery; 1 bridge-to-transplant, 1 bridge-to-HM3, 1 death (12.5%)	II-3

*: Level of Evidence (LoE) based on American Heart Association (AHA) Classification: Ⅰ = RCT/meta-analysis; Ⅱ-1= Evidence from well-designed RCTs with limitations; Ⅱ-2= Evidence from multicenter registries/cohorts; Ⅱ-3= Evidence from case series; Ⅴ = Expert opinion/reviews.

4.1. Pathophysiology of Pediatric LCOS: A Developmentally Unique Paradigm

The pathophysiology of LCOS in children undergoing congenital heart surgery represents a complex interplay of factors that differ substantially from adult post-cardiotomy shock (2).

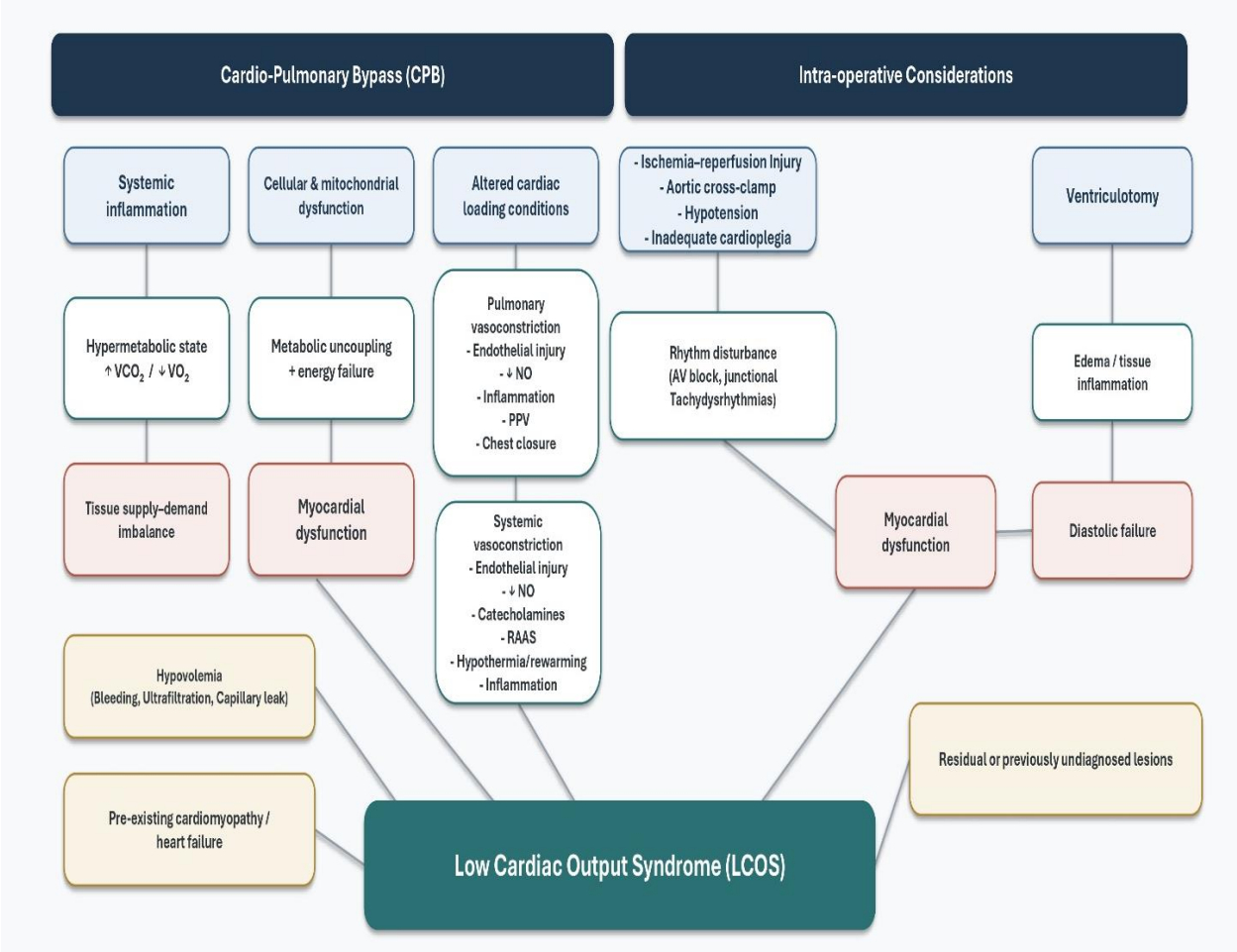

Figure 2. A schematic illustrating the interrelated mechanisms that converge to cause LCOS in pediatrics. (NO= Nitric oxide, PPV= Positive Pressure Ventilation, RAAS= Renin–Angiotensin–Aldosterone System)

4.1.1. Myocardial and Developmental Factors

-Myocardial immaturity: The neonatal myocardium contains fewer myofibrils, reduced sarcoplasmic reticulum density, and increased dependence on trans-sarcolemmal calcium flux for excitation-contraction coupling. This results in limited contractile reserve and heightened vulnerability to ischemia-reperfusion injury (11, 12).

-Biventricular versus single-ventricle physiology: The response to surgical stress differs dramatically between biventricular repair and single-ventricle palliation. The single-ventricle circulation, particularly after Norwood or Fontan procedures, is uniquely vulnerable due to parallel circulation, volume overload, and limited flow reserve (13).

-Cardiopulmonary bypass effects: CPB in children triggers a robust systemic inflammatory response syndrome (SIRS) characterized by capillary leak, myocardial edema, and vasoplegia. The magnitude of this response is often proportionally greater in smaller children due to a larger circuit surface area relative to blood volume (14).

4.1.2. Lesion-Specific Considerations

-Tetralogy of Fallot: Right ventricular dysfunction secondary to ventriculotomy, residual right ventricular outflow tract obstruction, or pulmonary regurgitation (2).

-Dextro-transposition of the great arteries: Post-operative left ventricular (systemic right ventricle after atrial switch) or right ventricular (after arterial switch) dysfunction depending on the repair type (15).

-Total anomalous pulmonary venous connection: Vulnerability to pulmonary hypertensive crises and right ventricular failure (16).

-Single-Ventricle Physiology and Staged Palliation:Patients with single-ventricle physiology represent a uniquely vulnerable subgroup, with distinct hemodynamic challenges at each stage of palliation (17, 18):

Ⅰ) Norwood stage (neonate): Following the Norwood procedure, the single right ventricle must support both systemic and pulmonary circulations in parallel. The combination of volume overload, increased afterload, and myocardial immaturity predisposes to early LCOS. Maintenance of a balanced pulmonary-to-systemic flow ratio (Qp: Qs ≈ 1:1) is critical; any deviation, whether due to pulmonary overcirculation (leading to coronary steal and systemic hypoperfusion) or undercirculation (resulting in hypoxemia), can precipitate LCOS.

Ⅱ) Glenn/BDCPA stage (4–6 months): After superior cavopulmonary anastomosis, pulmonary blood flow becomes passive and dependent on low pulmonary vascular resistance (PVR). Elevated PVR, due to acidosis, hypoxia, atelectasis, or pulmonary hypertensive crises, immediately compromises pulmonary blood flow, leading to increased SVC pressure, decreased preload to the single ventricle, and consequent low cardiac output. Meticulous PVR management is essential.

Ⅲ) Fontan completion (18–36 months): Total cavopulmonary connection creates a circulation entirely dependent on passive pulmonary flow. Cardiac output becomes exquisitely sensitive to A) Elevated PVR (from infections, aspiration, or high airway pressures), B) Impaired ventricular function (diastolic dysfunction is common), C) Atrioventricular valve regurgitation (increasing preload and compromising forward flow), and D) Thrombotic complications (pulmonary emboli, fenestration closure). The Fontan circulation has no subpulmonary ventricle; thus, any increase in PVR or decrease in ventricular function directly reduces cardiac output, often manifesting as low mixed venous saturation, ascites, and protein-losing enteropathy. Management priorities include maintaining low PVR (optimal sedation, ventilation strategies, pulmonary vasodilators), preserving ventricular function, and strict volume balance (avoiding both hypovolemia and fluid overload) (17,18).

Table 2. Hemodynamic targets and LCOS triggers in single-ventricle staged palliation

Stage	Age	Key Physiology	Hemodynamic Targets	Common LCOS Triggers	Management Priorities
Norwood	Neonate	- Parallel circulation - RV supports both circulations	- Qp:Qs ≈ 1:1 - SvO_2 >65% - SBP >65 mmHg VIS <15	- Pulmonary overcirculation (Qp: Qs >1.5) - Hypotension - acidosis	- Optimize Qp:Qs - Maintain SVR - Milrinone for afterload reduction
Glenn/BDCPA	4–6 months	Passive pulmonary flow (SVC→PA)	- PVR <2 WU·m² - SvO_2 >70% - CVP <15 mmHg	- Elevated PVR (atelectasis, hypoxia, infection) - Low preload	- Minimize PVR (sedation, paralysis, ventilation) - Maintain preload - Avoid hyperventilation
Fontan	18–36 months	- Total cavopulmonary connection - Passive pulmonary flow	- PVR <2 WU·m² - CVP <15 mmHg - SvO_2 >65% - Fenestration open if needed	- PVR elevation - Ventricular dysfunction - AV valve regurgitation - Thrombosis	- Maintain low PVR - Fenestration - Afterload reduction -Anticoagulation - Diuresis if volume overloaded

4.1.3. The Triad of LCOS Pathophysiology

Synthesizing current evidence, pediatric LCOS results from three interrelated mechanisms (2):

1.Direct myocardial injury: From intraoperative ischemia, inadequate myocardial protection, or surgical manipulation.

2.Altered loading conditions: Secondary to residual lesions, arrhythmias, or changes in pulmonary/systemic vascular resistance.

3.Systemic inflammatory response: CPB-induced capillary leak, myocardial edema, and vasoplegia.

4.2. Early Recognition and Monitoring Strategies:

Timely identification of LCOS is paramount to prevent progression to irreversible end-organ damage. Based on the reviewed literature, a multi-modal monitoring approach is essential (3).

4.2.1. Clinical and Hemodynamic Monitoring:

A comprehensive cardiovascular exam, including heart rate, blood pressure, capillary refill time, pulse volume, urine output, and peripheral temperature, is crucial.

On the other hand, invasive pressure monitoring with central venous pressure (CVP), left atrial pressure (LAP) when available, and arterial pressure appears to be key factors. Interpretation of filling pressures must account for lesion-specific physiology (Table 1).

Table 1. Interpretation of Filling Pressures in Pediatric Post-Operative Patients

Pressure	Causes of Elevation	Causes of Reduction
Right Atrial Pressure (RAP)	RV dysfunction, pulmonary hypertension, tamponade, fluid overload	Hypovolemia, vasoplegia
Left Atrial Pressure (LAP)	LV dysfunction, mitral valve disease, pulmonary vein obstruction, fluid overload	Hypovolemia, pulmonary vein obstruction (paradoxical)
Pulmonary Artery Pressure (PAP)	Pulmonary hypertension, left heart obstruction, increased pulmonary flow	Hypovolemia, RV outflow obstruction

4.2.2. Laboratory Monitoring

Some studies report that serum lactate levels in the normal or decreasing range suggest stable hemodynamics. On the contrary, increasing lactate or decreasing base excess indicates inadequate oxygen delivery (3).

Moreover, continuous central venous oxygen saturation ($SvcO_2$) monitoring using catheters such as PediaSat has been shown to reduce mechanical ventilation duration, vasopressor requirements, and ICU length of stay in pediatric cardiac surgery patients. However, it did not significantly affect lactate clearance in a 2025 randomized trial (10). In support of this, an Arteriovenous oxygen saturation difference ($A\text{-}VO_2$ gradient) greater than 30% indicates inadequate cardiac output relative to metabolic demand (3).

To further illustrate this point, Near-infrared spectroscopy (NIRS) provides continuous, non-invasive assessment of regional tissue oxygenation and complements systemic monitoring (3).

4.2.3. Advanced Hemodynamic Monitoring

Beyond standard clinical and laboratory parameters, advanced monitoring techniques provide real-time, dynamic assessment of cardiac output and tissue perfusion:

- Transpulmonary thermodilution (e.g., PiCCO or VolumeView): Provides continuous cardiac index, stroke volume variation, and

extravascular lung water. While validated in children, it requires central venous and arterial access. It may be less accurate in intracardiac shunts (e.g., residual VSD, Fontan). Used primarily in older children and adolescents.

-Echocardiographic functional assessment: Point-of-care echocardiography enables:

A) LVOT velocity-time integral (VTI) as a surrogate for stroke volume (normal: >10–12 cm in infants; >15–18 cm in older children)

B) Tissue Doppler imaging (TDI) of myocardial velocities (e.g., S', E', A') to assess systolic and diastolic function

C) Assessment of pulmonary artery pressures from tricuspid regurgitation velocity

D) Evaluation of the inferior vena cava diameter and collapsibility to estimate volume status (though less reliable in ventilated patients).

4.2.4. Near-infrared spectroscopy (NIRS) trend monitoring

While covered earlier, we emphasize that sustained deviations of >10–15% from baseline, or a difference of >20% between cerebral and somatic (e.g., renal) NIRS values, suggest regional hypoperfusion and should prompt immediate hemodynamic optimization.

4.2.5. Arteriovenous oxygen gradient (A-VO_2)

Calculated from arterial and central venous ($SvcO_2$) oxygen saturation. A gradient >30% indicates inadequate cardiac output relative to metabolic demand. It is a reliable marker of LCOS even when lactate remains normal.

Combining these tools provides a comprehensive, multi-parameter assessment that enables early detection and severity stratification of LCOS, allowing timely therapeutic escalation before irreversible end-organ injury occurs.

4.2.6. The Vasoactive-Inotropic Score (VIS)

Serial VIS calculations provide an objective, quantifiable measure of pharmacological support requirements. It has been validated as a predictor of outcomes in pediatric cardiac patients.

Table 4. Clinical and laboratory parameters for LCOS monitoring and interpretation.

Parameter	Normal Values (Pediatric)	LCOS Threshold	Interpretation	Action
Lactate	<2.0 mmol/L	4.0 mmol/L (persistent)	Inadequate oxygen delivery - Tissue hypoperfusion	- Optimize CO - Consider escalation
SvO_2	70%	<60% (or ↓ >10% from baseline)	Decreased oxygen delivery relative to demand	- Increase CO - Treat hypoxia/anemia
A-VO_2 gradient	<30%	30%	Inadequate CO despite normal SvO_2	Increase CO
NIRS (cerebral)	65%	<55% or ↓ >15% from baseline	Cerebral hypoperfusion	- Optimize BP - Optimize CO - Optimize ventilation
NIRS (renal)	60%	<50% or >20% difference from cerebral	Renal/splanchnic hypoperfusion	- Consider fluid bolus - Use of inotropes
LVOT VTI	- 10–12 cm (infants) - >15–18 cm (older)	↓ >20% from baseline	Decreased stroke volume	- Volume loading - Inotrope support
VIS	≤10 (stable)	20 (escalation trigger)	Increasing pharmacological support	Consider tMCS consultation

4.2.7. echocardiography

Point-of-care echocardiography is indispensable for assessing ventricular function (systolic and diastolic), identifying residual hemodynamic lesions (shunts, obstructions, regurgitation), evaluating pericardial effusion/tamponade, and guiding hemodynamic management.

4.3. Pharmacological Prevention and Management

4.3.1. Prophylactic Strategies

The PRIMACORP study established the role of prophylactic Milrinone in reducing the incidence of post-operative LCOS in infants undergoing cardiac surgery (3). More recently, attention has focused on the comparative effectiveness of different inodilators.

4.3.2. Levosimendan versus Milrinone: 2025 Meta-Analysis Evidence

A 2025 systematic review and meta-analysis including 1,200 pediatric patients (600 Levosimendan, 600 Milrinone) undergoing cardiac surgery demonstrated a significant reduction in LCOS incidence in the Levosimendan group compared with the Milrinone group (relative risk 0.67, 95% CI 0.54–0.83, p=0.001). Also, there is no significant difference in cardiac index, ejection fraction, or stroke volume index between groups. Furthermore, as a secondary benefit, Levosimendan is associated with shorter mechanical ventilation duration, ICU stay, and overall hospitalization (6).

4.3.3. General Pharmacological Approach

Management of established LCOS follows a stepwise approach: (1)*Optimize preload:* Fluid boluses 2–5 mL/kg, titrated to filling pressures and clinical response. (2).*Enhance contractility:* Epinephrine, Dopamine, Dobutamine based on hemodynamic targets. (3).*Reduce afterload:* Milrinone, sodium nitroprusside, phenoxybenzamine. (4).*Minimize oxygen consumption:* Adequate sedation, analgesia, and neuromuscular blockade when indicated. (5).*Treat arrhythmias:* Junctional ectopic tachycardia (JET) is common postoperatively and may require cooling, antiarrhythmics, or pacing.

4.4. Temporary Mechanical Circulatory Support in Pediatric LCOS

When pharmacological support fails to restore adequate cardiac output, tMCS must be considered promptly. Recent evidence has shown significant advances in pediatric tMCS, particularly through multicenter collaborative data (4, 5, 7).

4.4.1. Extracorporeal Membrane Oxygenation (ECMO)

ECMO remains the most commonly used tMCS modality in children, particularly for those weighing <20–25 kg, who constitute the majority of the congenital heart surgery population. According to the 2024 ELSO registry report (20), ECMO was used in over 5,200 pediatric patients with cardiac failure, representing approximately 85% of all pediatric mechanical circulatory support episodes. The survival-to-discharge rate was 48% for post-cardiotomy patients, with significant variation by age (infants <1 year: 42%; older children: 55%) and center volume (high-volume centers: 52% vs. low-volume: 41%, p=0.03).

Indications for ECMO in the post-cardiotomy setting include (3, 20):

-Failure to wean from cardiopulmonary bypass (approximately 30% of cases)

-Refractory LCOS unresponsive to maximal medical therapy (VIS >20–30)

-Post-cardiac arrest as rescue therapy (ECPR), with survival rates of 35–40% if initiated within 30 minutes of arrest

-Progressive end-organ dysfunction (lactate >4 mmol/L, oliguria, rising creatinine)

The timing of ECMO initiation critically

impacts outcomes. A multicenter analysis of 1,200 ECMO runs demonstrated that survival decreased from 55% to 32% when ECMO was initiated >6 hours after the onset of refractory LCOS ($p<0.001$) (20). Earlier deployment, before the onset of irreversible end-organ damage, is consistently associated with improved survival. However, premature initiation exposes patients to unnecessary risks, highlighting the need for precise triggers and multidisciplinary decision-making.

Common complications of pediatric ECMO include bleeding (32%), acute kidney injury requiring dialysis (28%), infection (18%), neurological injury (15%), and limb ischemia (10%). The risk of these complications is higher in neonates, patients requiring open chest management, and those on prolonged support (>14 days) (20).

We emphasize that, based on current evidence, ECMO remains the standard of care and first-line mechanical support for the vast majority of pediatric patients with refractory LCOS.

4.4.2. Impella in Pediatric Patients: The ACTION Collaborative Experience

The Impella percutaneous axial flow pump, extensively used in adults, has increasingly been applied in older children and adolescents. The literature provides the largest multicenter datasets to date.

- ACTION Network Multi-Institutional Outcomes (2025) (4):In a cohort study, 150 pediatric patients from 29 institutions (April 2018–November 2024) were investigated. The median age of participants was 15.3 years (IQR 13.4–17.2), the median weight was 62.9 kg (IQR 51.0–79.7), and the smallest patient weighed 19.0 kg. The device types were Impella 5.5 (53%), Impella CP, and Impella 2.5. The implant frequency increased from 0.4/month (2018) to 2.5/month (2024), with the approach via the axillary artery (40.1%) and the femoral artery (29%). The diagnoses of the patients were dilated cardiomyopathy (57.3%), graft dysfunction (14.7%), and congenital heart disease (13.3%). Of this, 25.3% required ECMO before Impella; 76% used ECMO and Impella in tandem. The outcomes showed positive clinical effect in 89.3% (32.7% explanted for recovery, 32% bridged to heart transplant, and 23.3% transitioned to durable VAD). In contrast, adverse event consequences included 28% experienced major bleeding, infection, device malfunction, or stroke; risk 2.3× higher in patients lower than 35 kg ($p=0.02$).
- ACTION Experience with Impella+ECMO (2024) (7): Another preliminary multicenter case series was conducted on 20 patients supported with VA-ECMO + Impella (ECPELLA). The patients had a median age of 15.6 years and a median weight of 65.7 kg. The patients' diagnoses were dilated cardiomyopathy/myocarditis (45%), CHD (20%), and graft failure (20%). This study had some major adverse events, such as hemolysis (50%) and bleeding (20%). Unfortunately, the mortality rate was 10% (2 patients) in the study population. Outcomes at explant showed 45% recovery, 40% transitioned to durable VAD, and 5% transplanted.
- Adolescent ECPELLA Series (2025) (5): From 2016 to 2024, a single-center retrospective case series (preliminary data) was conducted on 8 adolescents (13–18 years, 40–59 kg) with VA-ECMO + Impella. The indications were myocarditis (4 patients), graft rejection (one patient), post-repair heart failure (one patient), metabolic cardiomyopathy (one patient), and arrhythmia-induced (one patient). The duration of temporary mechanical circulatory support was 8 days (2–20) for Impella and 7 days (4–32) for ECMO. The main outcomes showed that 5 patients

(62.5%) recovered myocardial function and weaned; one patient bridged to transplant, another transitioned to HeartMate-3, and only one patient died on support. Table 5 presents evidence in pediatrics for temporary mechanical circulatory support.

Table 5: Summary of Key Contemporary Evidence in Pediatric LCOS (2020-2025)

Study/ Network	Year	Design	Population (N)	Key Findings	LOE*
ACTION Impella (4)	2025	Multicenter registry	150 (29 centers)	89.3% positive outcomes; complications 2.3× higher if <35 kg	II-2
Levosimendan Meta-analysis (6)	2025	Systematic review/meta-analysis	1,200 (pooled)	LCOS reduction vs milrinone: RR 0.67 (p=0.001)	I
ACTION ECPELLA (7)	2024	Multicenter case series	20	45% recovery, 40% bridge to durable VAD	II-3
Adolescent ECPELLA (5)	2025	Single-center series	8	62.5% myocardial recovery	II-3
$SvcO_2$ Monitoring RCT (10)	2025	Randomized trial	120	Reduced ventilation/ICU stay; no lactate clearance difference	II-1

*** LOE:** Level of Evidence (Adapted from AHA classification)

4.4.2.1. Contraindications and Complications of Impella in Pediatrics

While Impella offers potential benefits, careful patient selection is critical. Based on the ACTION registry and manufacturer recommendations, absolute and relative contraindications include (4, 7):

Ⅰ) Absolute contraindications:

-Weight <20 kg (due to vessel size; the 19 kg patient in the ACTION series was a single exceptional case)

-Severe aortic regurgitation (the axial pump increases LV unloading but exacerbates regurgitant flow)

-Severe peripheral vascular disease or occlusive femoral/axillary artery disease

-Ventricular septal defect without adequate separation (right-to-left shunting)

-Mechanical aortic valve or severely calcified aorta

Ⅱ) Relative contraindications:

-Weight 20–35 kg (associated with 2.3× higher complication rate, as shown in ACTION data)

-Prosthetic vascular grafts in the access route

-Significant thrombus in the LV

-Severe coagulopathy or bleeding diathesis

Complications reported in the pediatric Impella series (4, 7) consist of:

A) Major bleeding: 28% (primarily gastrointestinal, cannula site, and intracranial), particularly higher in patients <35 kg (p=0.02).

B) Hemolysis: 50% in ECPELLA patients, requiring frequent laboratory monitoring (LDH, haptoglobin, plasma-free hemoglobin).

C) Vascular complications: Limb ischemia, access site thrombosis, and dissection (incidence ~15%, significantly higher with femoral vs. axillary access).

D) Infection: 12% (cannula-related and bloodstream infections)

E) Device malfunction: 8% (pump thrombosis or malposition, requiring repositioning or exchange)

F) Stroke/TIA: 5% (most likely embolic).

In the ACTION series, the complication rate was 2.3-fold higher in patients <35 kg (p=0.02), underscoring the importance of appropriate patient selection, vascular

imaging before insertion, and institutional experience. We recommend that Impella use in smaller children be restricted to experienced centers with dedicated mechanical circulatory support teams.

4.4.3. Device Selection Algorithm in Pediatric LCOS

Based on a pragmatic framework derived from the available evidence, we propose the following preliminary framework for device selection, which should be viewed as a synthesis of published data and expert interpretation rather than a formal guideline (3, 4, 5, 7):

Ⅰ) Weight <20–25 kg: ECMO is the primary option (consistent with ELSO registry data)

Ⅱ) Weight 20–40 kg: ECMO remains the standard approach; Impella may be considered only in experienced centers with vascular expertise, based on limited case reports

Ⅲ) Weight>40 kg: Impella is a viable option for isolated LV failure, supported by preliminary ACTION registry data

Ⅳ) Biventricular failure + respiratory failure: VA-ECMO preferred (consistent with published consensus)

Ⅴ) Isolated LV failure: Impella alone may be sufficient (based on limited observational data)

Ⅵ) ECMO with inadequate LV unloading: Consider Impella addition (ECPELLA) as an emerging strategy, although evidence is preliminary.

We emphasize that this framework reflects the authors' synthesis of currently available (mostly observational) data and should not be interpreted as a formal practice guideline. Formal consensus from professional societies is urgently needed.

4.5. The Multidisciplinary Team: Essential for Success

Successful management of pediatric LCOS requires a well-coordinated team, including (3, 8): Congenital cardiac surgeons, Pediatric intensivists, Pediatric cardiologists, Cardiac anesthesiologists, perfusionists, specialized cardiac ICU nurses, Respiratory therapists, Pharmacists, social workers, and family support.

4.6. Strength of Evidence and Limitations of Included Sources

It is important to acknowledge that the evidence base for pediatric temporary mechanical circulatory support remains limited, with few high-quality randomized controlled trials. Among the included studies, only the PRIMACORP trial (3) and the levosimendan meta-analysis (6) represent Level I evidence (randomized controlled trials or high-quality systematic reviews). The ACTION Network registry reports (4,7) and the adolescent ECPELLA series (5) are currently available as preliminary registry data or conference abstracts and have not yet undergone full peer review. These sources, while providing the largest multicenter datasets currently available in pediatrics, should be interpreted as hypothesis-generating rather than practice-changing. Throughout this review, we have explicitly labeled the level of evidence for each key study to help readers distinguish between definitive and preliminary data. All treatment algorithms and recommendations derived from preliminary sources are clearly identified as such.

5. Discussion

5.1. Pathophysiology and Clinical Integration

Pediatric post-cardiotomy LCOS is distinct from adult shock, characterized by myocardial immaturity, lesion-specific hemodynamics, and an exaggerated systemic inflammatory response to CPB (2). The "triad of insults"—direct myocardial injury, altered loading conditions, and SIRS—provides a

practical framework for bedside decision-making. Management must be tailored to the specific congenital heart disease substrate and developmental stage, rather than extrapolating from adult protocols.

5.2. Evolution of Monitoring

Monitoring has shifted from reactive to predictive strategies. Continuous $SvcO_2$ monitoring reduces ventilator days and ICU stay by enabling earlier detection of hemodynamic compromise. However, it does not improve lactate clearance (10). NIRS provides trend monitoring of regional perfusion, with interventions triggered by sustained deviations from baseline (3). Point-of-care echocardiography enables trained intensivists and nurses to assess ventricular function and volume status in real time.

5.3. Pharmacological Advances

A 2025 meta-analysis demonstrates that levosimendan reduces LCOS incidence by 33% compared to milrinone, with shorter ventilation and ICU stays (6). Its calcium-sensitizing mechanism enhances contractility without increasing myocardial oxygen consumption, which may be particularly advantageous in the vulnerable neonatal myocardium. However, heterogeneity across studies and the lack of differences in cardiac index suggest that the benefits may derive from non-contractile effects. Levosimendan's longer half-life complicates rapid titration. It represents a valuable addition for high-risk patients. However, it should not yet replace milrinone as the standard of care pending further trials.

5.4. Temporary Mechanical Circulatory Support

ECMO remains the cornerstone for patients <20 kg (3). The timing of initiation is critical—earlier deployment, before irreversible end-organ injury, improves outcomes. LV unloading is essential to prevent distension and pulmonary edema, driving interest in active venting strategies, including atrial septostomy, surgical vents, and Impella addition (5, 7).

5.4.1. Temporary Mechanical Circulatory Support

Despite the emergence of newer technologies, ECMO remains the most widely used and accessible form of temporary mechanical circulatory support for children with refractory LCOS. According to the most recent ELSO registry report (20), ECMO is used approximately 8–10 times more frequently than all other forms of pediatric mechanical support combined. It is particularly true for infants and children weighing <20–25 kg, who constitute the majority of patients with congenital heart disease.

The survival-to-discharge rate for pediatric post-cardiotomy ECMO in the 2024 ELSO report was 48%, with outcomes significantly influenced by the timing of initiation. Earlier deployment, before the onset of irreversible end-organ injury (particularly acute kidney injury, hepatic dysfunction, or neurological insult), is consistently associated with improved survival (3, 20).

However, ECMO is not without limitations. Common complications include bleeding (32%), infection (18%), limb ischemia, and neurological injury. The requirement for systemic anticoagulation poses particular challenges in the immediate post-operative period, and the large circuit prime volume can exacerbate systemic inflammatory response and capillary leak in smaller children. Despite these limitations, ECMO remains the default strategy for most pediatric centers, particularly those without access to specialized Impella programs.

The decision to initiate ECMO requires careful multidisciplinary deliberation, with clear triggers including:

-Failure to wean from cardiopulmonary bypass

-Refractory LCOS unresponsive to maximal pharmacological support (VIS >20–30)

-Cardiac arrest with reversible cause (ECPR)

-Progressive metabolic acidosis (lactate >4–5 mmol/L) despite optimization.

We emphasize that ECMO should remain the first-line mechanical support for the majority of pediatric patients, and that Impella and other emerging devices should be viewed as adjuncts or alternatives in selected older children and adolescents, rather than replacements for ECMO.

Preliminary data from the ACTION collaborative suggest positive outcomes in 89.3% of patients receiving Impella (32.7% recovery, 32% bridge to transplant, 23.3% transition to durable VAD) (4). However, these findings are derived from registry data awaiting peer review and should be interpreted cautiously. Currently, Impella should be considered an emerging and investigational option in pediatrics, rather than a standard of care, particularly in patients weighing <35 kg where complication rates are significantly higher.

ECPELLA (ECMO + Impella) has shown promising recovery rates of 45–62.5% in small case series and preliminary reports (5,7). However, the limited sample sizes (n=8 and n=20) and the preliminary nature of these data preclude definitive conclusions. The high hemolysis rates (up to 50%) underscore the need for larger, peer-reviewed studies before this strategy can be broadly recommended.

Device selection should be weight-based: ECMO for <20 kg; ECMO as standard for 20–40 kg with selective Impella use in experienced centers; and Impella alone for isolated LV failure or ECPELLA for biventricular failure in patients >40 kg (3,4,5,7).

The device-selection framework we propose is based on the limited available data and represents our synthesis of published evidence, registry reports, and clinical experience. We acknowledge that this framework has not been externally validated and should not replace clinical judgment or institutional protocols. Prospective validation and formal consensus development are urgently needed.

5.5. Multidisciplinary Team

Multidisciplinary team management is essential (3,8). Nurses provide continuous bedside insights into trends and subtle changes. Perfusionists bring expertise in circuit design, flow dynamics, and anticoagulation. Structured handover from OR to ICU with checklists reduces errors. Family communication and support from social workers and palliative care specialists are critical components of comprehensive care.

5.6. Methodological Considerations

This scoping review intentionally did not use GRADE, as scoping reviews map literature rather than provide appraised recommendations (9). The heterogeneity and observational nature of pediatric tMCS evidence make formal grading impractical and potentially misleading.

5.7. Long-Term Outcomes After Pediatric LCOS and tMCS:

While the immediate survival and weaning rates are important, the long-term outcomes of children who survive LCOS deserve equal attention. Survivors of severe LCOS requiring tMCS face significant long-term sequelae:

A) Neurodevelopmental impairment: The incidence of cognitive delay, motor deficits, and behavioral disorders in survivors of pediatric tMCS is estimated at 30–50%, with higher rates in neonates, those with chromosomal abnormalities, and patients who experienced prolonged hypoperfusion or cardiac arrest (3, 20). Routine

developmental surveillance and early intervention programs are essential.

B) Myocardial functional recovery: Among Impella patients with positive outcomes, 32.7% recovered sufficient myocardial function to permit explantation without transplant (4). However, recovery may be incomplete, with many survivors developing chronic ventricular dysfunction, arrhythmias, or exercise intolerance in the long term. Serial echocardiographic and cardiac MRI follow-up is indicated.

C) Quality of life and psychosocial impact: Survivors of complex congenital heart surgery and tMCS often experience reduced quality of life, including physical limitations, feeding difficulties, hospital readmissions, and family psychosocial burden. A multidisciplinary approach—including psychology, social work, and palliative care, should extend beyond the acute phase.

D) Resource utilization and healthcare costs: Prolonged tMCS is associated with extended ICU stays, multiple readmissions, and significant healthcare costs. Long-term cost-effectiveness analyses are lacking but essential for informing resource allocation in healthcare systems.

We recommend that centers managing pediatric LCOS develop structured follow-up pathways that include:

-Routine neurodevelopmental assessment at 1, 2, and 5 years of age

-Annual cardiology follow-up with echocardiography and functional assessment

-Psychology and neuropsychology support for school-age children

-Family psychosocial support and counseling

Future registry-based research should incorporate longitudinal outcomes, including functional status, quality of life, and neurocognition, to complement the currently available survival data.

5.8. Future Directions

Key unanswered questions include the optimal timing of tMCS initiation, the comparative effectiveness of devices, the development of smaller Impella devices for infants, and the integration of palliative care principles. Collaborative networks like ACTION are essential for generating evidence. To overcome the predominance of observational data, we propose a pragmatic, registry-based randomized trial comparing Impella vs. ECMO in children 40-80 kg with isolated LV failure, using a stepped-wedge or cluster-randomized design with the ACTION network.

5.9. Comparison with Existing Reviews

Previous reviews of pediatric LCOS have focused either exclusively on pharmacological prevention (19) or on ECMO outcomes (20). To our knowledge, this is the first scoping review to integrate developmental pathophysiology with the complete spectrum of contemporary temporary mechanical support, including the latest Impella and ECPELLA data from multicenter collaboratives. Our findings extend those of Smith et al. (21) by providing weight-based device-selection algorithms derived from the largest available pediatric cohorts and complement the ACTION network's individual publications by synthesizing their cumulative experience within a unified physiological framework.

5.10. Limitations

Several limitations warrant consideration. First, as a scoping review, we did not formally assess risk of bias or grade the quality of evidence using instruments such as ROBINS-I or GRADE, consistent with the methodological purpose of scoping reviews (9). Second, despite systematic searching, we cannot exclude publication bias favoring positive outcomes in device registries. Third, the rapid evolution of device technology

means that findings from 2020-2025 may not fully reflect ongoing innovations. Fourth, several of the included studies (particularly the ACTION Network reports and the adolescent ECPELLA series) are currently available only as conference abstracts or preliminary registry data. We have explicitly labeled these as 'preliminary' throughout the Results section and have tempered our conclusions accordingly. However, readers should be aware that these data may change after full peer review and publication.

This review establishes a reference baseline for device performance in the 2020-2025 era, against which future innovations can be benchmarked. Fourth, our restriction to English-language publications may have excluded relevant non-English evidence. Finally, findings from specialized centers with established mechanical support programs may not be generalizable to centers developing new tMCS services.

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